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MATERIALS AND METHODS OF CONSTRUCTION IN LIGHT STRUCTURES

By Adolf Rohrbach

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By Adolf Rohrbach

I wish first to thank the W.G.L. (Wissenschaftliche Gesellschaft für Luftfahrt) for inviting me to speak on the problems of light construction.

At first I did not know just what this subject was intended to cover but, after corresponding with members of the lecture committee of the W.G.L., I decided to discuss principally material and production problems.

Lecturing on these practical questions is a little difficult for me as the representative of an airplane-construction firm, since my knowledge is naturally one-sided and, being still at the beginning of the development of airplane construction, it is not yet easy to formulate general principles.

Since I cannot therefore give a comprehensive and accurate description of the methods of production of wood and metal airplanes employed in foreign countries and by other German firms, I will simply present my own views, hoping that just this one-sidedness will call forth a fruitful discussion and corresponding contributions from the representatives of other firms regarding other methods of construction.

The many conditions which must be satisfied in the construction of an airplane, fall into two principal groups, namely, conditions of construction and of use.

The most important conditions of use are, e.g., all the factors affecting the performances, such as structural safety, one or more wings, one or more engines, aspect ratio, flight characteristics, arrangement of seats, landing gear, floating stability (of seaplanes), bulkheads, strength of bottom stiffeners, protection against corrosion, etc.

*"Entwurf und Aufgaben des Leichtbaues." From Yearbook of the Wissenschaftliche Gesellschaft für Luftfahrt, Dec., 1926, pp. 64-78.

to 400%, as shown by the following figures: Berlin, 1.25 gold marks; Stuttgart, 0.98; Copenhagen, 1.70; Italy, 0.40; England, 1.35.

Political influences may affect the cost of production similarly to the above-mentioned differences in wages. In this connection your attention is called to the position of the French firms, some of which manufacture on a very large scale, and to most of the German and many of the English firms, which now make only single airplanes or very small series.

In the course of time, however, the rates of exchange and the wage levels of the different countries will approach one another near enough so that the production costs will be everywhere approximately the same, provided the different efficiencies of the individual workmen, as also the different taxes, special levies, duties, etc., are considered.

The W.G.L. has hitherto devoted itself almost exclusively to aerodynamic or strength problems. In this respect, we have already made so much progress that a reduction of 10% in the drag or in the weight of an airplane represents a remarkable improvement.

As regards production problems, however, we have made so little progress that differences of 100% or more in the production time are almost the rule for airplanes which, at first glance are seemingly similar and which, moreover, seem equally well adapted to their purpose.

As a scientific society, the W.G.L. can take no direct interest in the costs as such, but only in so far as they determine the limits for the application of scientific data with respect to the greatest possible fulfillment of purposes and practical development in particular directions, in which applied science must precede in order to assist in solving the aerodynamic and strength problems involved. This influence of the production problems has always been present, but in the future it will be increasingly decisive for the success of certain designs, because they will differ so little in their suitability for a given purpose, but probably very much at first in their production costs.

I will now discuss briefly a few questions which af-

because a good metal airplane generally differs as a whole or in its exterior dimensions from the corresponding wood airplane, so that a skeptic can have doubts as to whether the better performance of the metal airplane is not ascribable to the more favorable dimensions or to the better weight ratio.

Duralumin or Steel?

Corresponding to the specific weights of duralumin and steel, tension members made of the latter are first equivalent to duralumin members of the same weight at a tensile strength of 110 kg/mm² (156,460 lb./sq.in.).

Different duralumin parts are generally joined by duralumin rivets of the same strength, so that such junctions involve only the weakening of the rivets. In this respect steel construction is less favorable because there are no rivets of 110 kg/mm² tensile strength, but ordinarily of only 30-40 kg/mm² (42,670 to 56,890 lb./sq.in.). Hence relatively many rivets must be used to join such steel parts and, in order to provide sufficient rivet area, more for steel than for duralumin. If the cross section of the steel member is to be fully utilized, there must be an enlargement of the rivet field at the junction place in order to provide space for all the rivets, which in turn denotes a similar loss in weight. In order therefore to preserve the equal weight of the whole steel structure, the steel would need to have a strength of about 130 kg/mm² (185,000 lb./sq.in.) with respect to this loss. Since the tools are not sufficiently stronger than such hard structural steel, much time would be required for the work, which would be accompanied by great wearing of the tools.

Moreover the cross sections of such steel members are very small, and they must therefore be made in the form of hollow sections or profiles with respect to an adequate inertia moment, the result being a very thin wall. Such profiles must generally be strengthened by all possible kinds of longitudinal corrugations, in order to prevent local buckling. Such profiles are very difficult to join together and could never be used in practical machines.

Since the hollow members mostly consist of several parts joined by longitudinal rows of rivets, another difficulty in connection with the joining is occasioned by

Open or Closed Profiles?

Open sections or profiles are made by passing strips of sheet metal between suitably shaped rollers. In preparing small quantities for experimental purposes (up to several hundred motors), it is cheaper to use a drawplate, thus saving expense for tools and apparatus.

Closed sections or profiles are about 20% more expensive than open ones, since they must consist of at least two open profiles with longitudinal riveting. Even duralumin tubes are considerably more expensive (40-60%) than duralumin profiles, because they are relatively brittle and, between the drawing operations, must be repeatedly annealed in salt baths, which are likewise very expensive on account of the great heat consumption. Many duralumin tubes must be heated 30-40 times during the course of their production.

The junctions of closed profiles are often heavier and more expensive than the junctions of open profiles with gusset plates. As compression struts, closed profiles are generally lighter than open profiles. This advantage is often nullified, however, by the greater weight of the junctions. In our airplanes, therefore, we have increasingly restricted the use of closed profiles. Open profiles can also be more readily protected against corrosion than closed ones, the inside of which can neither be inspected nor painted.

The danger of corrosion is of especial importance for seaplanes, on which, for the same reason, all duralumin parts must be painted before being riveted together. In order to effect a still further improvement, we have recently adopted measures to make all spaces between the profiles and adjacent parts so tight that water cannot get between any structural parts, but can only wet their exterior surfaces and evaporate without doing any harm. In particular, every closed profile on a seaplane constitutes a corrosion risk, chiefly, of course, in the parts constantly in contact with the water. Even in the most careful construction, it is difficult to prevent the water from getting between the metal sheets and the closed profiles. Even if this is prevented on the new seaplanes, the parts will surely be sprung in use, so that water can get in and cause corrosion without being noticed at first.

Where the material has to be profiled for the obtention of greater buckling strength, the profiles should be open. From this there results a type of construction similar to that of a ship, with a supporting covering, and the necessity of making the wing and tail of separate riveted parts assembled by screws and bolts.

The suitable location of the junctions greatly affects the cost of production. Formerly we screwed the wing spars to the stubs projecting from the fuselage. We then constructed a triple wing girder, the middle piece of which was secured by screws in a recess in the top of the fuselage and to which, moreover, both the other pieces were screwed. Subsequently we screwed the middle section of the three-part wing to the top of the fuselage and joined the outer wing spars to it as before. In later airplanes we returned to the former method of joining the wings to the stubs projecting from the fuselage. Fittings of high-resistance steel were used at the junctions.

Despite the fact that chrome-nickel steel has quite a high electric tension as compared with duralumin, corrosion in these junctions can be entirely prevented by carefully painting the steel fittings with ocher, so that no water can get into the joints.

Although I consider the constructional method introduced by us, with smooth metal sheets and open profiles, as the simplest, I do not wish to be understood as not recognizing the advantages of wood airplanes or steel-tubing fuselages for special purposes. I regard all these other constructional methods, however, only as convenient transitional methods, which sooner or later will be gradually replaced by the simpler duralumin construction.

After these more general remarks, I will now try, by means of a few examples, to give you an idea of how we are endeavoring to reduce the cost of production. The factory can operate economically only when the material and all working instructions are carefully prepared. This means the presence of absolutely complete working drawings and lists of parts.

The working drawings must cover not only the principal parts, such as the wings and fuselage, but also all small parts, such as control rods, engine governor, instrument arrangement, floor supports, etc. Even the points

suited to small-scale production, it may be very economical in mass production. In mass production it is, of course, obvious that even expensive equipment may not ultimately greatly increase the cost of the individual airplane. Of course cheaper equipment would still further reduce this cost. Moreover, even an article in mass production can be superseded by better types, thus causing the loss of much capital through the scrapping of the expensive equipment while, in the contrary case, conversion of the factory would be greatly facilitated. Obviously the equipment for making a given type of airplane would always be more extensive and complete, the larger the series to be produced. The difference in cost between the equipment required for an airplane of simple design and one of more elaborate design will therefore always be relatively the same.

In individual construction, all the transverse frames, ribs, fittings, etc., are tested separately, in order that any defects may not be first discovered in assembling, when they would cause loss of time, or even later in the finished airplane, where they might do still more harm. The assembling is greatly accelerated by having all connections, bearings for the conduits, control rods, instruments and all the parts ready in advance. By such methods we have effected a saving of 30-50% in time.

All orders are calculated by a practical system and their corresponding production times compared. Thus a record is obtained of the work expended on the airplane itself and also of the "unproductive" work expended on the factory equipment. In like manner a record is kept of the time spent in the preparation of the working drawings. Thus all time-robbing methods were tested and in many instances were greatly simplified.

All changes in design are immediately introduced into the drawings. In order that this may not be overlooked, the head of the workroom calls attention in writing to all corrections and changes, which must then be made in the drafting room. A complete set of the drawings and lists of parts is filed for every airplane, so that, in connection with any subsequent experiences of this airplane, it is always possible to tell just how any given part was made.

The whole system of cooperation between the drafting,

When referred to equal weight, somewhat less than 60% of the working time used for the wing girder a was required for the wing girder b of the commercial airplane. This improvement extended to all parts of the wing girder, since the shares of the different working times were approximately equal for the girders a and b.

The greatest saving was probably in the assembling and riveting of the longitudinal walls, whereby working times in the ratio of 13/8 were attained. This improvement was effected, in the first place, by a simple stamping process, by which the edges of the openings in the longitudinal walls, corresponding to a template, were worked out by a stamping tool, and in the second place by machine riveting. (Figures 3 and 4.)

Figure 5 shows the longitudinal wall of a wing girder in which the diagonals are reinforced by riveted sections or profiles instead of by bending out the edges of the openings. The present method of bending out the edges of the openings according to a template is considerably more practical, however.

Table II gives the relative working times for the production of the whole wing, whose girders formed the basis of Table I.

Table II. Working Times for the Wings

Kind of work	Airplane a	Airplane b
Making wing girder	51%	55%
" leading-edge formers	10	11
" end-rib formers	7	7
" aileron "	10	9
" ailerons	18	6
" wing cap	-	8
Assembling wing	4	4
Total	100%	100%

If the working time for the whole wing is referred to equal weight, the saving for wing b, as compared with wing a, is only 31.5% against 40% for the girder alone. This is because the rounded wing tips, which we here made for the first time, are quite expensive. The time required for assembling the wing is quite small; much smaller, in fact, than the saving made in the individual parts due to

was introduced with the result that the working times were immediately reduced more than one-half. The improvement from g to h was then effected by a structural change which, unfortunately, I cannot yet describe for reasons connected with its patenting.

Similar examples could be mentioned in any desired number. For example, the working time for the production of externally similar floats was reduced 40% by the simplification of the frame and a practical method for the main fastening.

I think there is no need of further examples to show how great savings in working time can yet be made. I am confident that, even without very large-scale production, provided we obtain enough orders to maintain the factory personnel at the present number of several hundred, in a year or two we can attain working times of less than half the present fairly short ones. Metal airplanes, even when made on a small scale, will then cost considerably less than wooden ones do now.

In the W.G.L. lectures, problems are discussed from all standpoints and possibilities, as to how performance can be increased per unit weight of the airplane or per unit weight of fuel, etc. Therefore, I wish to thank the W.G.L. for this opportunity to discuss the possibilities of an hour of human work, which is, after all, our most valuable asset.

Comments

Engineer Spiegel.- Dr. Rohrbach's address is especially welcome, because it introduces pure production problems into the circle of those previously discussed before the W.G.L. Even though, as the speaker remarked, such questions have little to do with pure science, they still stand in mutual relations with the latter. Science, on the one hand, assigns certain tasks to the producer while, on the other hand, production problems often afford the incentive to new scientific researches.

It would therefore be very desirable in future to have such questions often discussed before the W.G.L., and thus develop a lively exchange of ideas between the different producers. How advantageous such an exchange of

These difficulties do not exist for large airplanes, where there is generally an abundance of time at one's disposal and where the cost of the first airplane is not generally so important, so that wood is eliminated.

As regards the relative merits of steel and light metal, I wish to call attention to the fact that, in various cases for the dimensioning of certain parts, not the strength but the stiffness is the determining factor. For example, in heavily loaded cantilever monoplane wings, torsion corrugations for ailerons, etc., the ratio

$$\frac{\text{modulus of elasticity or shear}}{\text{specific weight}}$$

is determinative for the behavior of the various metals with respect to stiffness.

This ratio is approximately the same for steel and light metal, whereby it must, however, be remembered that the modulus of elasticity always has approximately the same value of 2,150,000 for nearly all kinds of steel, even those of less strength. Hence if one is compelled, for the sake of rigidity, to make a part larger than would be necessary for strength alone, a poorer quality of steel of 50-60 kg/mm² (71,118 to 85,340 lb./sq.in.) can safely be used, without making the part heavier than light metal, with the advantage of being considerably cheaper.

As regards the advantages and disadvantages of open and closed profiles, I agree entirely with the speaker. It cannot be denied, however, that for very large airplanes, due to the given structural possibilities, the closed profile, especially in the form of tubes, may have decided advantages, when it is possible to avoid the disadvantages otherwise inherent in the closed profile. This can be easily accomplished by special constructional devices. The chief advantages of a tube over a combination of two open profiles are:

1. Greatest utilization of the cross section, especially for heavily stressed compression struts;

2. Elimination of the longitudinal seam;

3. Convenient workability and hence gradual adaptability of the cross section to the generated forces by simply screwing one section over another;

4. The butt joints can be made with simple screw

Director Hüttner.- I consider it a particularly happy thought of the W.G.L. to give one of our most prominent airplane constructors the opportunity to speak at this year's session on airplane material and production problems. This subject is especially appropriate for the present time, when our airplane industry, largely freed from the bonds of the London ultimatum, is on the threshold of a new phase of development. As compared with the industries of other countries, our German airplane industry is obliged to struggle for existence because, aside from a few sport airplanes, it can produce only commercial airplanes, since it is barred from the most important field, that of military airplanes. It must therefore stake everything on developing the field remaining to it as thoroughly as possible, a problem which will be solved only when it succeeds in an ever increasing extension of air traffic and in reducing the cost so that great numbers of our people will be enabled to travel by airplane.

The cost of flying depends chiefly on three factors: fuel consumption, original cost of airplane, and amortization. When calculated per passenger for all three of the factors a considerably less favorable result is obtained than for transportation by railroad or automobile. Airplane manufacturers and air-traffic companies must therefore cooperate to reduce these costs. The fuel problem may soon be solved favorably for German air traffic since, although Germany constitutes but a small part of the world's fuel market, there is just developing an advance of the powers on the German market, which betokens possibilities regarding its relative importance and which may again change Germany from an object to a subject of world politics. The work of the dye trust in obtaining liquid fuels from coal is becoming increasingly important and may yet make Germany independent of other countries for its fuel supply and considerably reduce the cost of the fuel.

In the second place, the cost of flying depends on the original cost of the aircraft and, through this, also on the third factor, the cost of amortization. Though the amortization of the engine is a more important factor than that of the cell, the latter constitutes, however, so large a percentage that any reduction in its cost must materially affect the cost of amortization. Hence, if air traffic is to be made cheaper, the airplane industry can make a substantial contribution by reducing the cost of production. Dr. Rohrbach has already indicated, in his very interest-

and made the condition that for equal weights the steel must have a strength of 40 (7.8 : 2.8) = about 110 kg/mm^2 (156,459 lb./sq.in.).

This condition, however, is not fully applicable, because the choice of a material can never be based on its tensile strength alone. At best this could be the case for purely tensile parts, and then only when the latter are not combined with other parts which could be affected by their deformation. An example will illustrate this. A cantilever girder is supported by a rod which is a purely tension member. On the assumption that the rod is a steel one with a tensile strength of 80 kg/mm^2 (113,788 lb./sq.in.) requiring the area F, a corresponding rod of duralumin would require an area of 2F. On this assumption and on the basis of the tensile strengths alone, we obtain for the steel rod a weight excess of 7.8 : (2 × 2.8) = 1.39 as compared with the duralumin rod. In order, however, for the girder to receive the same stresses in both cases, the deformation of both rods must be the same. Hence we must have $F_D = (220 : 70)\ F_S = 3.15\ F_S$ (the expression 220 : 70 representing the ratio of the moduli of elasticity of the materials compared).

Since the ratio of the specific weights is only 7.8 : 2.8 = 2.8, the aluminum rod, on the above assumptions, will be heavier to the amount of 3.15 : 2.8 = 1.12. If, therefore, the duralumin rod should be given only the same weight as the steel rod, then under certain conditions, a corresponding excess weight would have to be given the girder.

The above statement is likewise applicable to compression struts. Such a strut, if it satisfies the Euler formula, can be made lighter of steel than of duralumin. Even a girder subjected to bending stresses, in which some bending deformation is to be expected, can be made lighter of steel than of duralumin.

In lattice girders the lattices can well be duralumin, since the effect of their deformation on the total deformation of the girder is extremely small (See Schwengler, "Elastizitätstheorie im Eisenbau"). In an actual girder test, the deformation of the lattices was found to be only 5% of the total deformation.

An important factor in the choice of the materials is

and hence with the same tensile strength as the riveted material, are used, while it has long been customary in steel construction to use iron rivets considerably softer than the riveted steel. Consequently, the rivet-hole relations can in no case be less favorable for steel with iron rivets than for duralumin with duralumin rivets. The relation is unfavorable, however, for duralumin with iron rivets. As stated by the speaker, the Rohrbach Company uses steel for spar fittings. It is obvious that those steel fittings for duralumin can never be lighter than steel fittings for steel.

I would summarize my conclusions regarding the choice of materials as follows. The choice of building materials can be made only from consideration of the given static relations, economy and practical experience for each individual case. I assume it to be obvious that the whole material problem can relate only to the construction of highly stressed structural parts. As a matter of experience it is known that the weight of such parts constitutes about 8% of the dead load of an airplane and the time required to construct them, about 7% of the time required to build the whole airplane.

Former naval architect Baatz.- Dr. Rohrbach spoke on the question of airplane materials. On the one hand he compared wood and metal and, on the other hand, duralumin and steel. His contention is probably correct that the development of the airplane will follow the course of development of all other vehicles, cars, ships, etc., from wood to metal construction. This is due to the difficulty of obtaining sufficient wood of uniform structure for the production of any article on a large scale. As to what the metal of the future is to be, there is still a great divergence of opinion. Dr. Rohrbach compares steel having a tensile breaking strength of over 100 kg/mm^2 (142,235 lb./sq.in.) with aluminum alloys having a breaking strength of 40 kg/mm^2 (56,890 lb./sq.in.). The general fact that metal of specifically great strength unfortunately has a very small elongation, has compelled mechanical engineers in general to refrain from approaching the upper limit of strength and to prefer materials with a relatively great elongation. I recall, for example, that steel, with a strength of 50-60 kg/mm^2 (71,118 to 85,340 lb./sq.in.) and an elongation of 10-12%, can be produced cheaply in any desired quantity. Nevertheless, there is used in great quantities, in the construction of vehicles steel of low

al and steel, the light metal is never attacked. These experimental results are confirmed by experience.

Although I naturally agree with Dr. Rohrbach that entirely closed profiles do not wear as well in use as open ones, a good protective coat inside a closed profile lasts better than a like coat on exposed surfaces. Experience has shown that structural parts suffer most where, through lack of proper care, the protective coat is removed by mechanical injuries and fails to be renewed. It seems to be established that light-metal parts require the greatest attention, even in use.

Dr. Rohrbach's arguments were especially interesting as regards the possibility of reducing the production costs by suitable equipment. In general, the equipment increases the so-called unproductive capital. I would be grateful to the lecturer if he could tell us in what ratio the sum of the unproductive and productive capital is reduced by suitable equipment. It might be still more difficult to answer the second question, as to whether the cost reduction of a piece is due simply to the familiarization of the worker with the production method, or in what proportion it is ascribable to the equipment. I would appreciate having Dr. Rohrbach give us further information on this point.

Engineer Schrenk.- Thus far nothing has been said today concerning an important method of joining steel parts, namely, by welding.

I have just come from the welding session of the V.D.I. (Verein Deutscher Ingenieure) in Hamburg, where I learned how the process of welding is continually making progress in all fields of mechanical construction. It is by no means new in airplane construction. (See N.A.C.A. Technical Memorandum No. 453, "Welding in Airplane Construction," by A. Rechtlich and M. Schrenk.)

The advantages of welding are obvious, namely, the possibility of making the most difficult junctions with a minimum increase in weight, especially of joining tubes in the simplest way imaginable without increase in weight, and the economy of this method.

Many persons, however, entertain serious doubts as to the advisability of welding in airplane construction. They

all due to considerations regarding the suitability of the material, but that it is simply a question of the difficulty of obtaining wood in war time. In the event of war, however, the quicker and cheaper supply of wooden airplanes, in comparison with the use of metal, would play a decisive role, since the possible longer life of metal airplanes would be more than offset by their rapid destruction and by the types becoming obsolete.

2. The greater cost of a metal airplane cannot be due alone to the extensive preliminary work of a constructive nature. This is demonstrated by the fact that, in metal construction, the necessity of further division of the structure into many small parts directly affects the working times even in quantity production. For obvious reasons Dr. Rohrbach does not give the absolute working times in metal construction, so that no direct comparison is possible in this respect. An approximate idea can be obtained, however, from the prices of similar airplanes built on about the same scale. This applies, for example, to the Junkers K 16 and the Focke-Wulf A 16, the sale prices of which bear approximately the ratio of 2 : 1.

3. As regards weight, wood construction still has the advantage, naturally with the fulfillment of the same strength requirements. Here also we can compare Junkers K 16 and Focke-Wulf A 16. With the same engine (75 hp Siemans) the K 16 carries only one pilot and two passengers and has a correspondingly smaller wing area than the A 16, which carries one pilot and three passengers at a somewhat higher speed. Nevertheless, the ratio of the dead load to the pay load is about the same for both airplanes.

4. One of the fundamental faults which can be imputed to the light metals of to-day, is their fatigability under varying stresses, though the danger from this phenomenon has always been contested, especially in Germany, but without any counter-evidence. American and Dutch experiments show that, under some circumstances, the figures obtained for varying stresses (vibration strength) are only 40% of those for static loading. Though Dr. Rohrbach says that fatigue phenomena were observed only above the proportionality limit, there always remains the consideration that no absolute definition of the proportionality limit can be made for any material. It has been found that accurate measurements enable the recognition of very

warping, the only other consideration in connection with wood is the actual chemical changes or, in other words, the various kinds of foulness. Probably every one will admit, however, that even under the most unfavorable conditions (outside the tropics) any real foulness can be prevented for decades by suitable protective measures. For comparison it is not fair to use the still existing wooden airplanes from the time of the war, whose protecting coats were almost always very inadequate, due to the hasty war-time production.

6. Wood, of course, always has one other defect, namely, the lack of uniform strength. This results in a greater weight than would otherwise be necessary. This defect does not signify, however, because any weight comparison still favors wood.

7. Fireproofness is always claimed as an advantage of metal. Experience has shown, however, that the fire hazards of an airplane are not determined by the building material but by the engine fuel. So long as such inflammable fuels must be used, the danger, in case of fire, will consist in the large amount of fuel on board. The simultaneous burning of a few wooden parts does not appreciably affect the catastrophe.

8. If the problems of fatigue, corrosion and cost were all satisfactorily solved, I would immediately advocate metal construction. Furthermore, it cannot be denied that the preference for metal construction does not rest alone on technical grounds. The engineer has a certain instinctive fear of working with unfamiliar materials. From the laity, which in this case is the flying public, we often hear such expressions as "Metal does not go to smash."

It may also be added that, with a metal covering, the always necessary external stiffeners (e.g., corrugations) have, according to the latest experiments, a very unfavorable aerodynamic effect, in that they increase the drag by retaining the boundary layer of air. Such stiffeners are practically indispensable, however, with the necessary thinness of the metal covering. To shift them to the inside would involve great difficulties of a constructive nature.

I have tried to explain briefly why wood airplanes are at least not yet entirely obsolete and still compare favorably with metal ones for many uses.

that I am of the opinion that duralumin is better in a series of cases where Mr. Neubert thinks steel should be preferred.

It would take too much time to discuss all these details, which, after all, can be satisfactorily settled only by the experience of the next few years.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

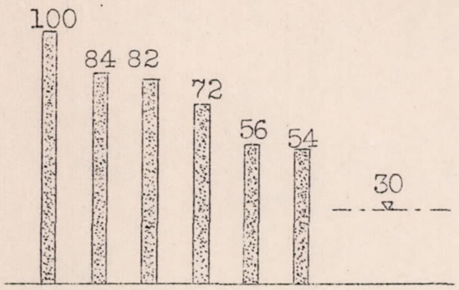


Fig.1

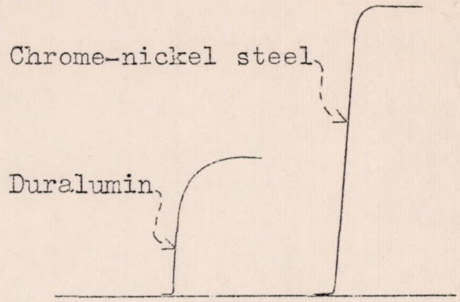


Fig.9

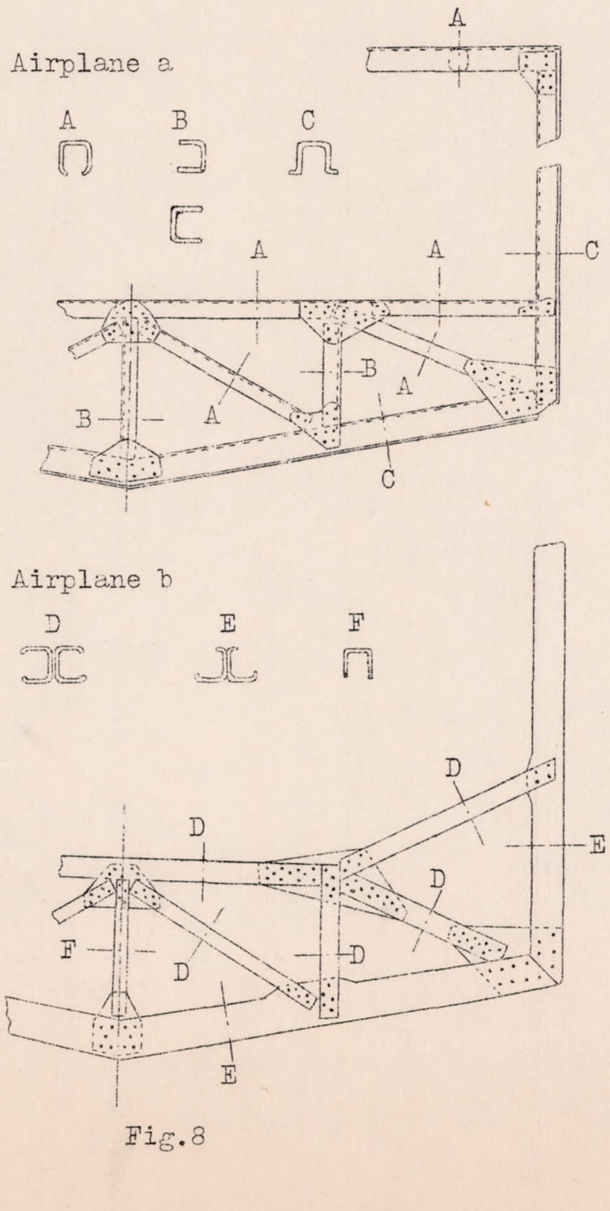


Fig.8

Fig.2

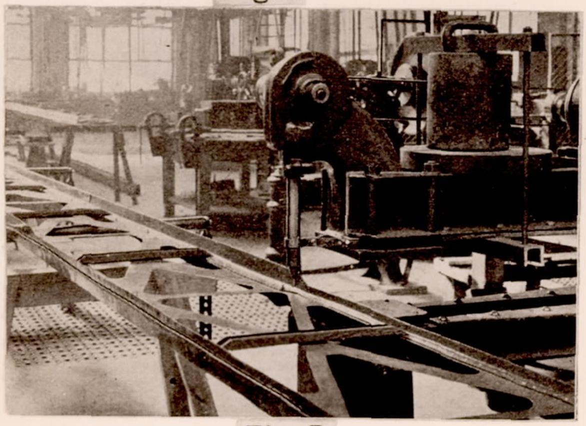


Fig.3

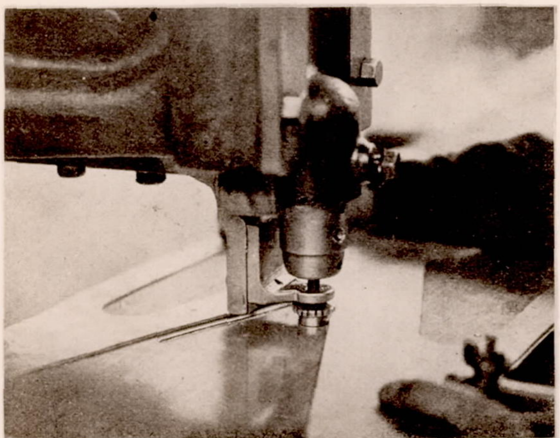


Fig.4

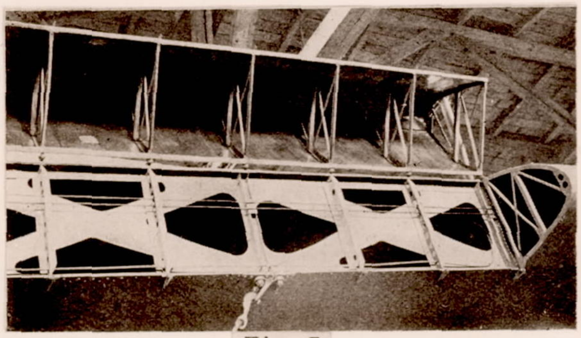


Fig.5

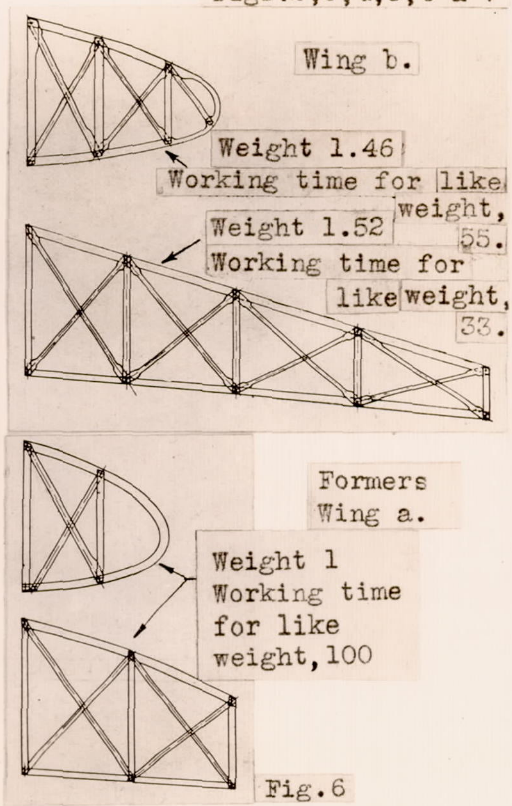
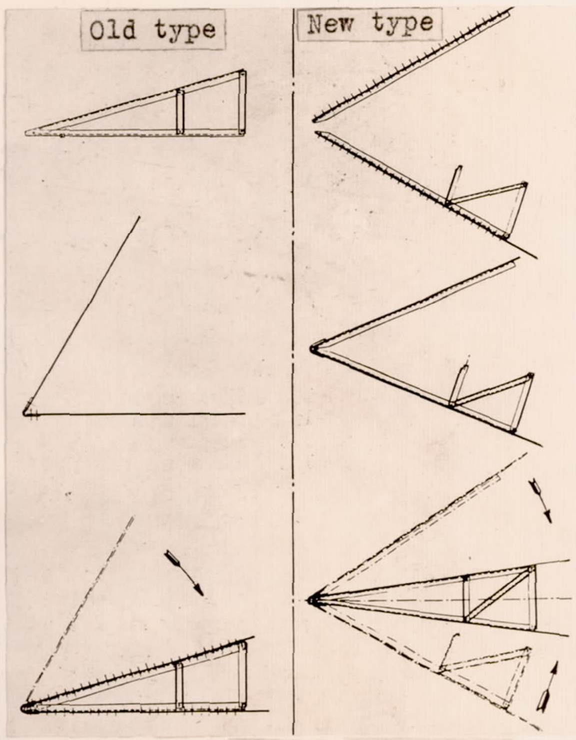


Fig.6



Weight 1

Working time for like weight,100

Fig.7

Weight 0.8

Working time for like weight, ?

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